An optical readout for a fiber tracker

M. Enkelmann, U. Werthenbach, G. Zech, T. Zeuner
University of Siegen, Department of Physics, 57068 Siegen, Germany

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Abstract

The performance of 16 and 64 channel photomultipliers coupled to scintillating fibers has been tested. The devices are sensitive to single photoelectrons, show little gain losses for magnetic fields up to 100 Gauss and have moderate optical cross-talk. The maximum channel to channel gain variations reach a factor two for the 16 channel version and a factor of four for the 64 channel PM. The measurements and simulations indicate that the photomultipliers are well suited for the light detection in fiber trackers.

1 Introduction

Scintillating fiber trackers constitute an interesting alternative to gaseous tracking detectors. Impressive progress has been made in the last years in both the quality of plastic fibers and the optical readout [1][2][3]. Fiber detectors avoid all the problems related to HV connections, sparks, electronic noise and pick-up in wire chambers and MSGC detectors. In view of these advantages the Hera-B [5] collaboration investigated the possibility to build an inner tracker of scintillating fibers as an alternative to a MSGC system. The fiber solution was finally abandoned due to the higher cost for a 150000 channel system and expected radiation damage. Nevertheless the results of the study are of possible interest for detectors operating under different experimental conditions.

Sensitive light detection is most efficiently achieved with photomultipliers. To reduce cost and space one has to use multichannel systems. Interesting alternative solutions provide multichannel PMs (MCPM)[1][6] built in standard technique, hybrid PMs (HPMT)[4] and visible light counters (VLPC)[3]. The latter provide by far the best photoefficiency of up to 80 %, but need cooling to below 10K. HPMTs allow for a finer spatial segmentation than MCPMs but require higher voltages and low noise amplification. In this article we present measurements with a readout system consisting of fibers coupled to small size 16 and 64 channel photomultipliers [7].

In the following sections we describe the setup, the simulation of the photon propagation and, finally, the measurements which concentrated on the investigation of the influence of magnetic fields and the cross-talk between channels.

Figure 1: Setup to measure the optical cross-talk.

2 The setup

We investigated multichannel photomultiplier tubes[1] [7] with 16 (M16) and 64 channels (M64) on a square sensitive area of $18 \times 18mm^2$. The tubes have bialkali photocathodes and metal channel dynode structures of front pad sizes of $4 \times 4mm^2$ (M16) and $2 \times 2mm^2$ (M64). The gaps between the dynodes of the matrix next to the window are $0.5mm$ (M16) and $0.3mm$ (M64) respectively.

Two different setups were used to measure the gain uniformity of the PM tubes and the optical cross-talk between adjacent channels. For the uniformity measurement a LED was operated at a distance of $30cm$ in front of the PM tube. The experimental arrangement for the cross-talk measurement (see Fig.1) consisted of a fiber guide mounted on a x-y-z-table which was moved under computer control across the PM window. The fiber was pressed by a spring onto the PM window.

In order to investigate the PM performance in magnetic fields, the PM was placed between two Helmholtz coils providing fields of up to 130 Gauss.

For the uniformity measurement the light was produced by standard green or blue LEDs. Short light pulses of the LED were generated by a special high current control circuit with adjustable pulse width. The optical cross-talk measurements were performed with scintillation light produced by β^- rays from a Sr^{90}-source in scintillating fibers.

The anode signals of the PM channels were amplified by standard NIM linear amplifiers with a fixed gain factor of 10. They were digitized by CAMAC ADCs coupled to a PC.

In the Hera-B experiment rates of $200kHz$ per channel are expected with average signal of 20 photoelectrons. The total photocurrent reaches $0.1mA$ for the 64 channel tube. To reduce the bleeder current an active voltage divider circuit for the dynodes (Fig. 2) was

[1]HAMAMATSU Photonics K.K., Japan

Figure 2: Active high voltage divider chain.

developed. Compared to a passive chain the current and correspondingly the number of HV power supplies and the heat dissipation can be reduced by a factor of five.

3 Simulation of photon propagation

Photons produced in a scintillating fiber are usually transferred to the photosensitive device via clear plastic fibers. The coupling of the fibers, reflection losses and the connection of the clear fiber to the PM affect the photoelectron yield and their lateral distribution. We have simulated these processes. For the numerical estimates we used refraction indices for the fiber (n_f), its gladding (n_{cl}), the PM window (n_w) and the photocathode (n_{ca}) of $n_f = 1.60$, $n_{cl} = 1.42$, $n_w = 1.53$ and $n_{ca} = 3.4$.

In the following we assume that the cross section of the fibers is circular. The trapping probability of the photons then depends on the distance of the production point from the surface. The trapping efficiency across the fiber is shown in Figure 3. The high efficiency for photons produced near the surface is due to the trapping of photons with rather large angles with respect to the fiber axis which then spiral along the surface in azimutal direction. The average trapping efficiency is $t = 1 - (n_{cl}/n_f)^2 = 0.213$. When the scintillating fiber is coupled to a clear fiber a large fraction of the spiraling photons is lost, the exact amount depending on the ratio of the diameters and the relative lateral positions of the axises. In the limit where photons are produced uniformly in the scintillating fiber, where the scintillating fiber is coupled axially at the center of the clear

Figure 3: Trapping efficiency across a scintillating fiber. Spiraling photons are lost when the scintillating fiber is coupled at the center of a clear fiber.

fiber and where the radius of the scintillating fiber is negligible compared to the clear fiber radius the trapping efficiency is reduced by a factor of about two: $t = 1 - n_{cl}/n_f = 0.113$.

Spiraling photons suffer from a high number of reflections at the fiber surface and thus have a higher probability to be lost than photons crossing the fiber axis. The losses depend on the quality of the surface and on the circular symmetry of the fiber. Often the cross section of so-called round fibers is in reality slightly elliptical and varying along the fiber. These losses which are difficult to estimate have also a positive aspect: They reduce the light divergence at the exit of the fiber.

For an efficient detection of minimum ionization particles in scintillating fibers with PMs of about 10% conversion efficiency a minimum scintillator thickness of about 1 to 2 mm is required, the exact value depending on the quality of the fiber and many other parameters related to the light detection system. Usually several thin scintillating fibers have to be coupled to one clear fiber to obtain an efficient and precise tracking. The minimum radius of the clear fiber which one chooses as small as possible is determined by the number and the cross section of the scintillating fibers to be coupled. On the other hand the maximum allowable cross section depends on the size of the PM channels, the window thickness and the light divergence at the fiber exit.

Figure 4 shows the effect of a tilt of the two axises in the coupling of the fibers. Losses start to become important only for rather large tilt angles.

The cross-talk to neighbouring PM channels is illustrated in Figure 5. The curves correspond to the fraction of photoelectrons collected by neigbouring channels surrounding one of the central pads. (Of course this fraction is lower for channels at the borders or corners of the PM.) The photons are produced in a bundle of seven scintillating fibers ($0.5mm$ diameter) coupled to one clear fiber of $3m$ length. The cross-talk becomes disturbing when the fiber diameter approaches the size of the square channel pads and is especially important for the standard window of $1.3mm$ thickness. For a signal of

Figure 4: Photon loss due to non-parallel coupling of the fibers. The solid curve represents the worst case, where the scintillating fiber is coupled at the center of a clear fiber. The upper curves correspond to fibers coupled at the periphery.

in average 10 photoelectrons and single photoelectron detection a channel multiplicity between 1.6 and 2.2 for a 1.5mm diameter fiber is expected.

The large cross-talk for small radia and negligible reflection loss is due to the increase of the number of spiraling photons when the coupled scintillating fibers cover the full cross section of the clear fiber. If sufficient light is available, the cross-talk can be reduced drastically by setting the threshold above the one photoelectron signal.

4 Measurements and results

We have tested six M16 tubes and three 64 channel prototypes with window thicknesses of 1.3mm, 1.0mm and 0.8mm.

4.1 Signals, amplification

The photomultiplier tubes have a fast time response. For the 16 channel device the pulse width for a single photoelectron is of the order of 1 to 2ns, the transit time spread is 0.3ns and the gain at the nominal voltage of 800V is $3 \cdot 10^6$ [2]. The numbers for the 64 channel tube are very similar except for a lower gain of $3 \cdot 10^5$ [2].

For optical fiber read-out in fiber trackers the photomultipliers have to work with very low light levels. Efficient detection of single photoelectrons is therefore required. Figure 6 shows pulse height distributions for single photoelectrons measured at different high voltage settings for the M16 type. At voltages above 900V the single photoelectron signal

[2] HAMAMATSU Product specifications.

Figure 5: Simulation of optical cross-talk for 64 channel PM as a function of the fiber radius.

is clearly separated from noise with a signal to noise ratio larger than ten. The M64 type has a smaller gain than the 16 channel version but a detection of single photoelectrons is also possible with an adapted readout system.

4.2 Uniformity

The channel to channel gain variations of the M16 and M64 photomultipliers were measured using a LED at a distance of $30cm$ from the PM which illuminated the whole photocathode. This configuration generated single photoelectron signals. All channels were read-out in parallel. The relative gain was calculated from the single photoelectron peak position in the pulse height distribution. The maximum gain variation between different channels of the same tube is less than a factor of two for the M16 PM's , for M64 PM's the variation is larger reaching a factor of four. The gain uniformity was measured for 6 PM's of the M16 type and the first two available prototypes of the M64 series. Figure 7 shows for both cases a typical gain histogram.

The mean gain variation of the six tested photomultipliers of the M16 type is 25%.

4.3 Position sensitivity and cross-talk

We have measured the position sensitivity of the PMs between the individual channels by scanning across three pads with a thin fiber of $50\mu m$ diameter, where light was injected

Figure 6: Single photoelectron pulse height distribution for 16 channel PM for different HV settings.

by a LED parallel to the axis. The response is rather uniform except for the gap region where the efficiency is reduced to an average of 60%. Thus the effective inefficient region is 0.2mm for the M16 and 0.1mm for the M64 tube.

In fiber tracker applications cross-talk between adjacent channels increases the apparent occupancy and produces fake signals. There are two possible sources for cross-talk: optical and electrical coupling.

Electrical cross-talk between adjacent dynode structures might occur during the electron multiplication processes. Up to the level of about ten photoelectrons electrical cross-talk was not observed in our measurements indicating that for applications with low light levels the electrical cross-talk is negligible. This is explained by path length variations and fluctuations in the light emission time, coincidences between several photoelectrons within the short transit time are unlikely in most cases.

The optical cross-talk was studied in a similar way as the sensitivity by moving a fiber of diameters of 1.5mm in steps of 100 μm across three dynode pads. However, the light was produced by irradiating a fiber bundle of seven scintillating fibers with a Sr^{90}-source to achieve a more realistic light distribution. The fiber bundle was coupled to a 2m long clear fiber which was connected to the PM. When the fiber is centered at a pad the neigbouring channel receives a fraction of 0.023 of the light (Fig. 8). Thus for four adjacent channels and a ten photoelectron average signal the channel multiplicity will be about two for a single photoelectrons threshold. This effect is especially disturbing since adjacent PM channels will not always correspond to adjacent fibers in the tracking detector.

Figure 7: Uniformity of the response of the channels for the 64 and the 16 channel PMs.

Figure 8: Relative photon yield as a function of the fiber position for two different window thicknesses. Adjacent channels detect 2.3% (1.3mm window) and 0.9% (0.8mm window).

To reduce the optical cross-talk we asked the PM supplier to decrease the entrance window thickness of the photomultiplier tubes to the minimum thickness which is technically possible. We received two prototype tubes with entrance window thicknesses of 1.0mm and 0.8mm. The cross-talk was reduced by a factor 2.5 for the 0.8mm thick window.

Our simulations (Fig. 5) predict for the two cases cross-talks of 0.05 (0.8mm window) and 0.13 (1.3mm window) for four adjacent channels and negligible reflection losses and correspondingly 0.005 and 0.06 when we assume that we loose a fraction of 0.001 for each photon reflection. The measurements (0.035) and (0.09) are located in between these predictions.

4.4 Behaviour in a magnetic field

At Hera-B the photomultipliers would have to be operated in regions with magnetic fields of several Gauss up to one Tesla. The gain of conventional photomultipliers is strongly affected by magnetic fields. As a result of the deflection of the electrons by the magnetic field in MCPMs in addition to reduced gain increased cross-talk might be expected.

The influence of a magnetic field on the PM performance was measured with fields up to 100G in all three directions with respect to the PM. We used single photoelectron signals. The magnetic field behaviour of the M16 and M64 types is very similar as expected because both tubes have the same metal channel dynode structure except for different lateral dimensions. Figure 9 shows the relative anode current for the 64 channel PM as a function of the magnetic field in the x-, y- and z-directions where the z axis

Figure 9: PM signal as a function of the magnetic field strenth.

coincides with the PM axis. The PMs are rather insensitive to magnetic fields. Within the precision of our measurement there is no effect for fields parallel to the y-axis. For the two other field orientations the PM signal is reduced to 80% (z-axis) and 70% (x-axis). About half of the loss is due to a gain reduction, the remaining fraction is loss in efficiency probably due to the deflection of the first photoelectron.

A position scan with and without magnetic field showed no difference in the amount of cross-talk. Thus the MCPMs can well be operated in magnetic fields below $100G$.

5 Conclusions

We have studied the possibility to use multichannel photomultipliers to read-out scintillating fiber trackers. The device is well suited for this purpose. It is fast, sensitive to single photoelectrons and can be operated in magnetic fields up to about 0.01 T. No electric cross-talk was observed. The optical cross-talk is of the order of 10% for the $1.3mm$ version and single photoelectron detection for fiber diameters near the pad dimensions. It was reduced by a factor 2.5 by replacing the $1.3mm$ window by a $0.8mm$ version. The measured cross-talk is compatible with the simulations which also show that it depends strongly on the amount of reflection losses in the fibers. The gain variations from channel to channel are rather large for the 64 channel tube and require individual off-line corrections for applications where the analog signal has to be recorded.

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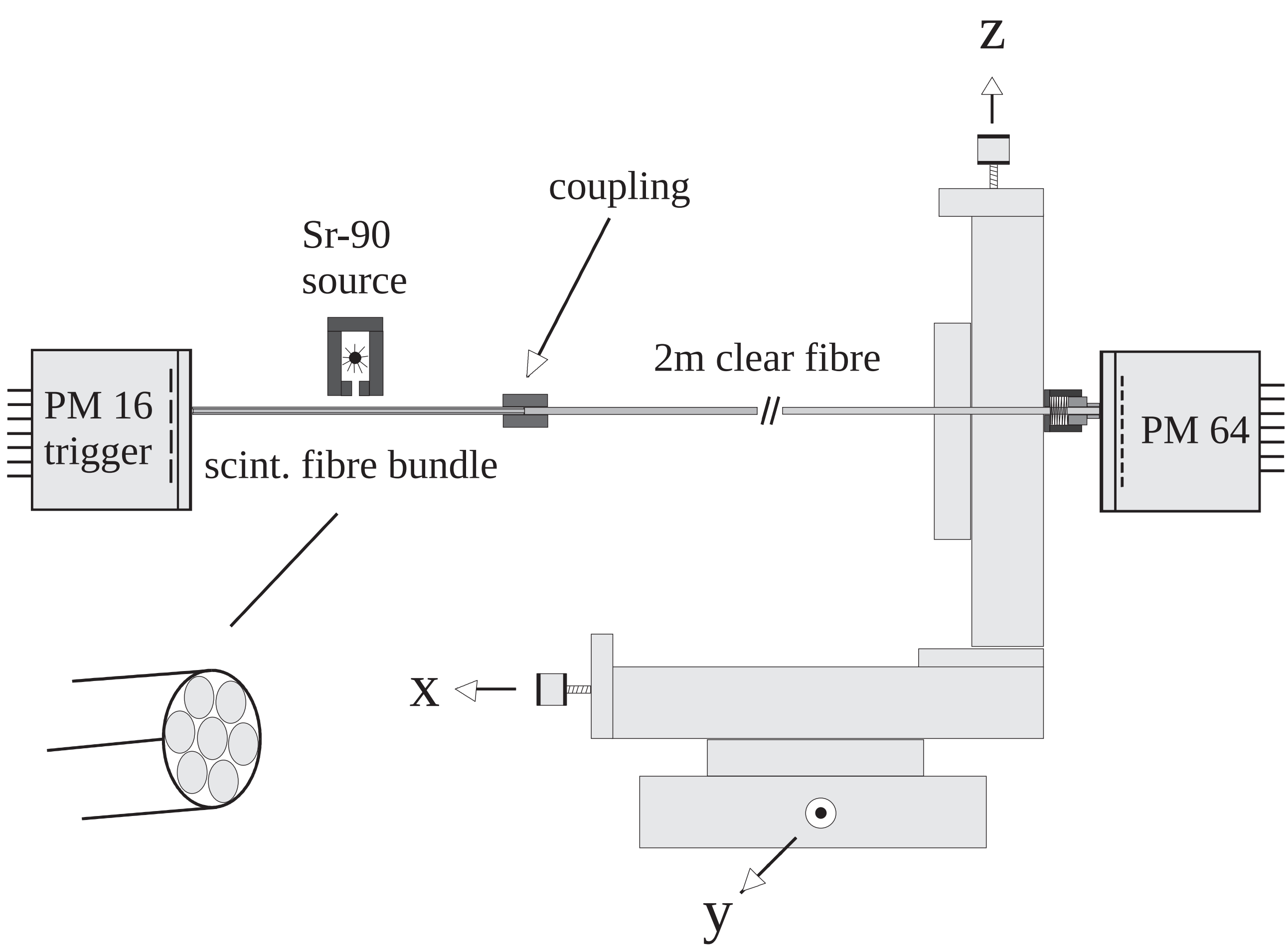
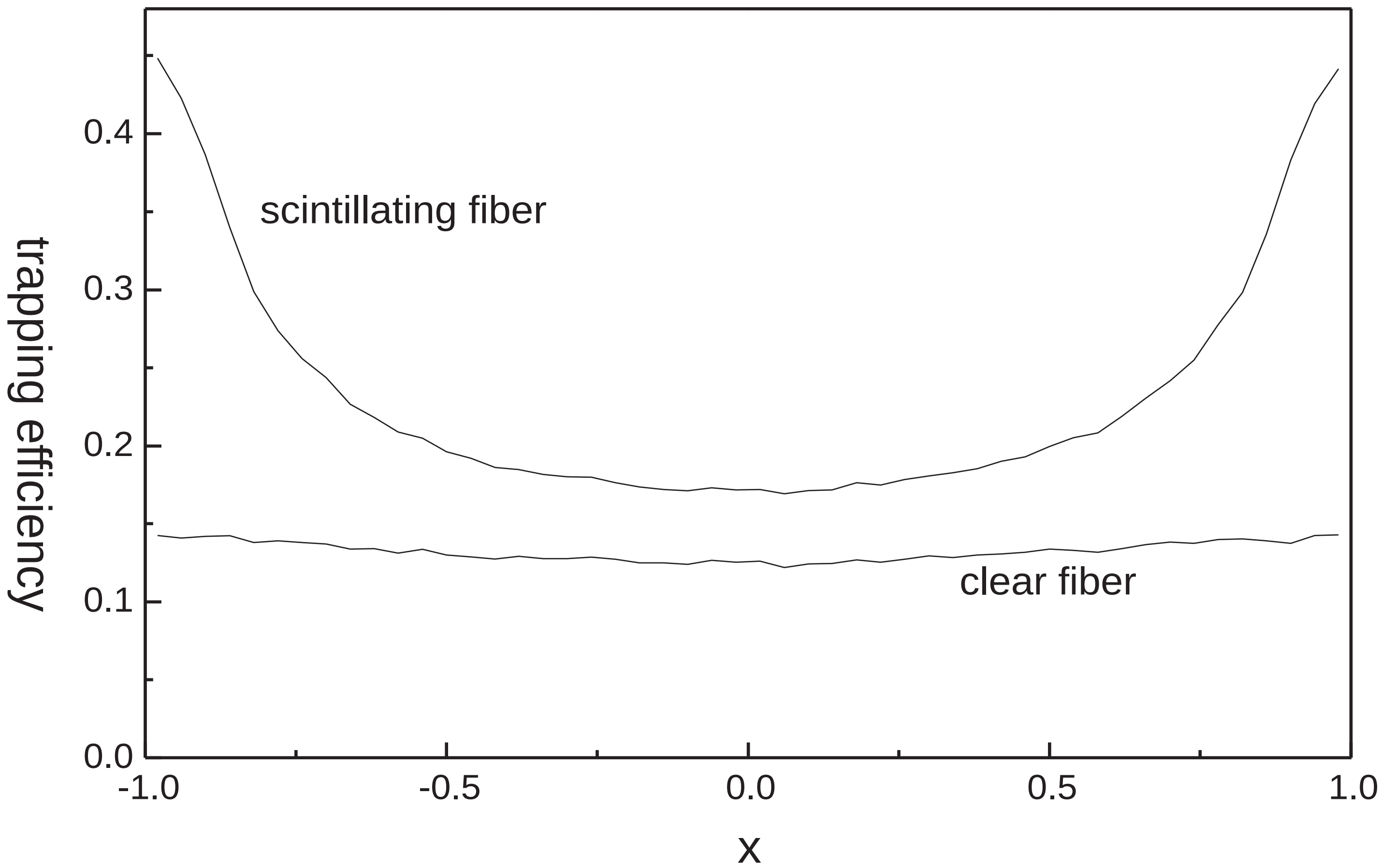
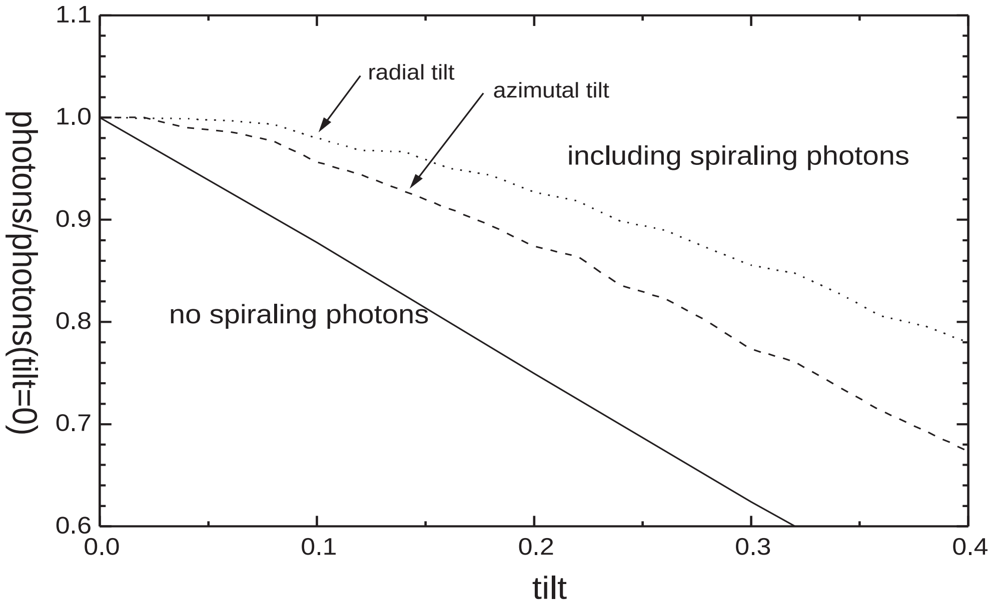
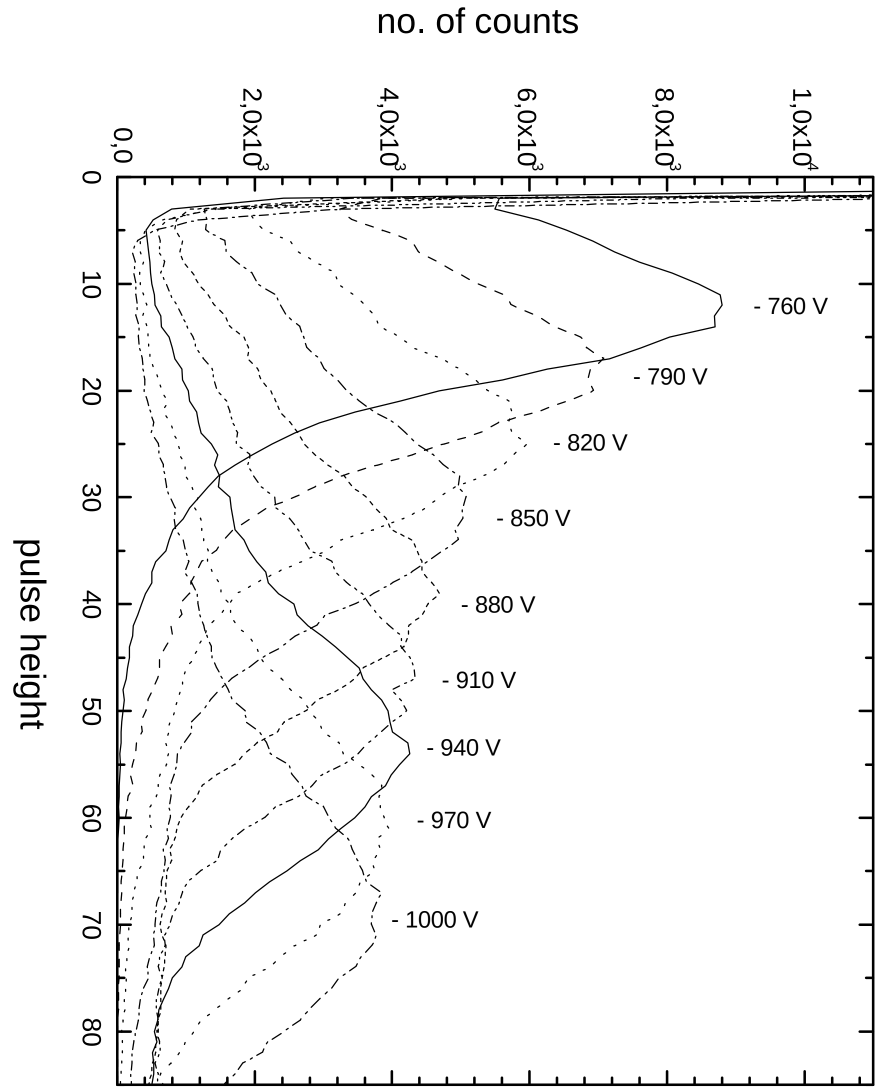


z
coupling
Sr-90
source
2m clear fibre
PM 16
trigger
scint. fibre bundle
PM 64
x
y



trapping efficiency
0.0
0.1
0.2
0.3
0.4
scintillating fiber
clear fiber
-1.0
-0.5
0.0
0.5
1.0
x


radial tilt
azimutal tilt
including spiraling photons
no spiraling photons
photons/photons(tilt=0)
tilt
1.1
1.0
0.9
0.8
0.7
0.6
0.0
0.1
0.2
0.3
0.4



no. of counts
pulse height
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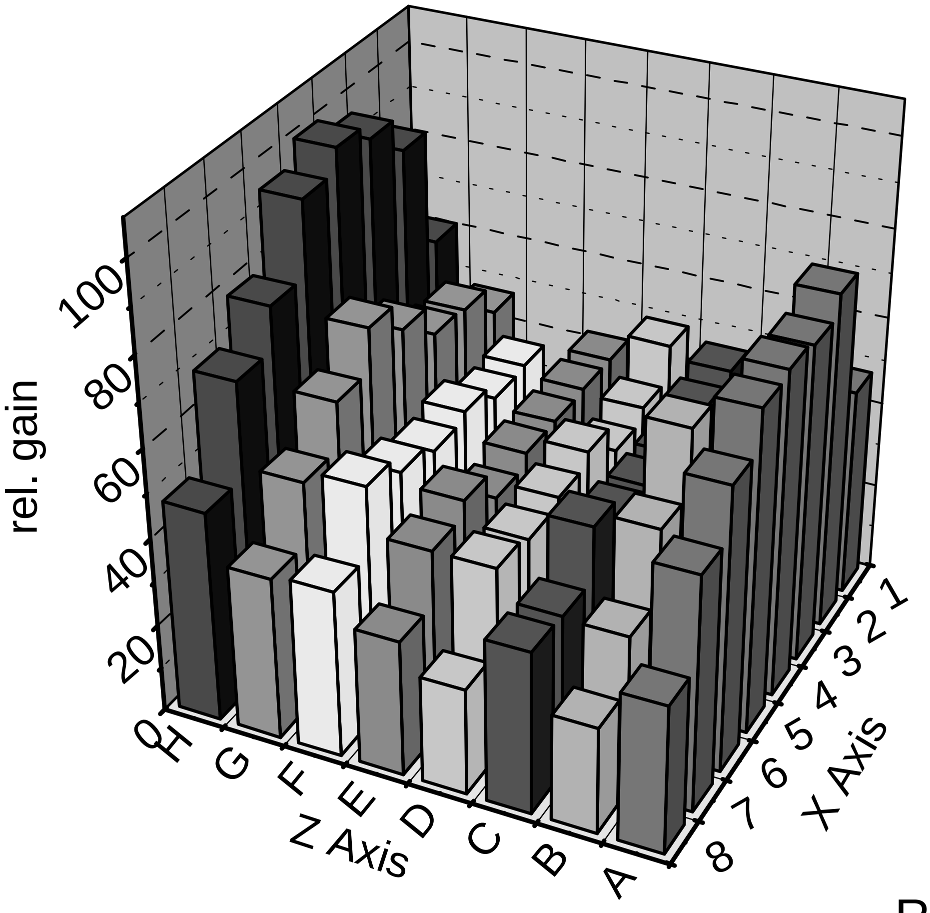
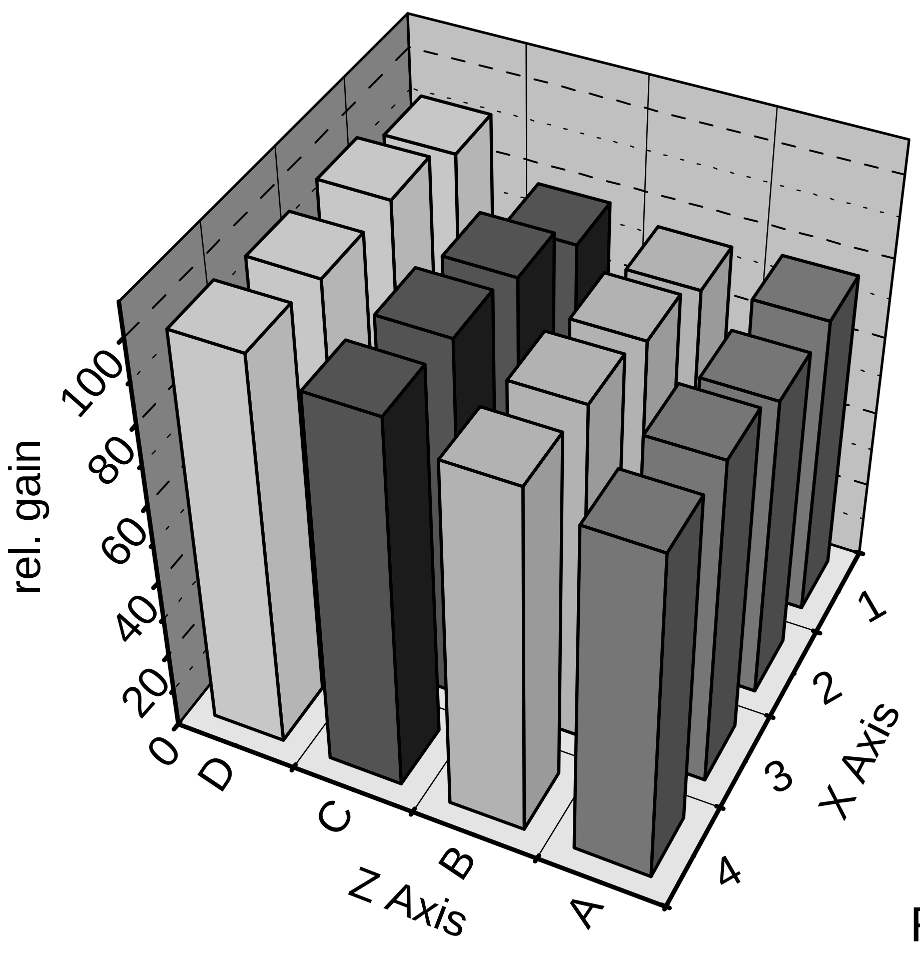
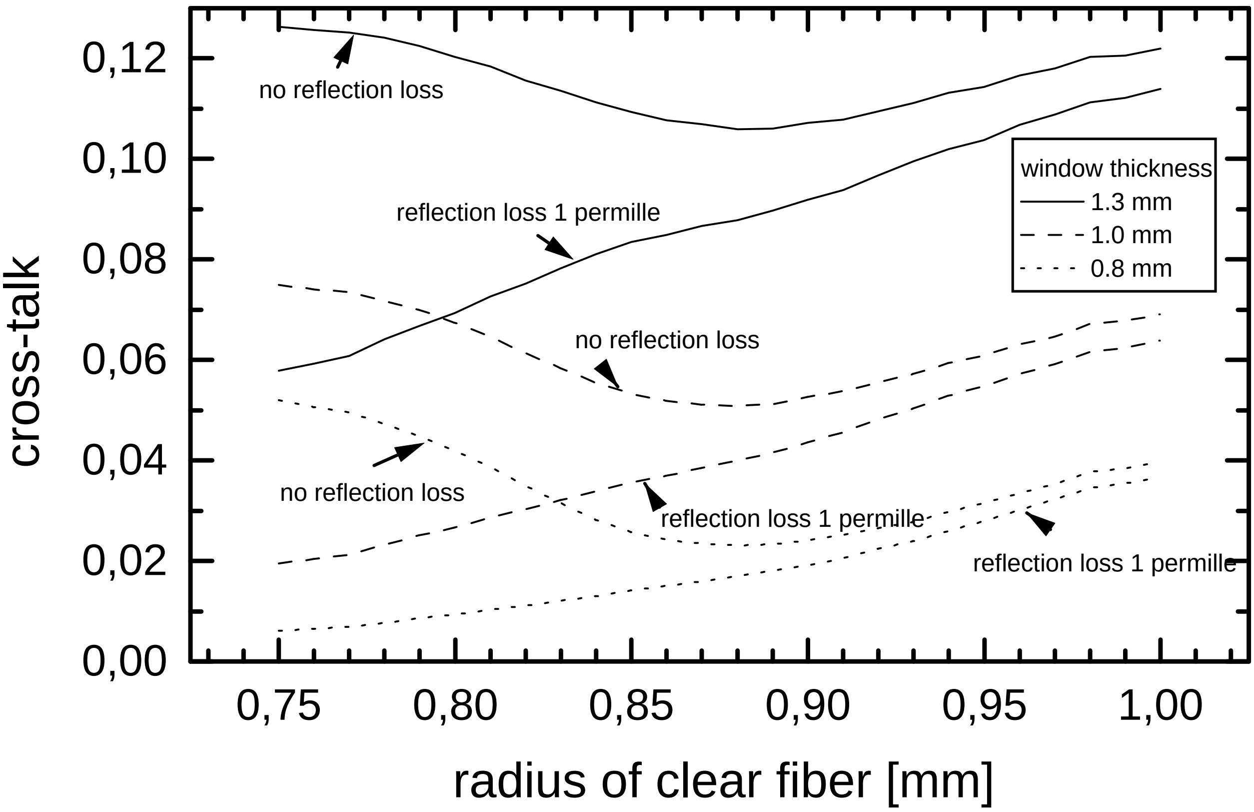
4,0x10^3
6,0x10^3
8,0x10^3
1,0x10^4
0
10
20
30
40
50
60
70
80
- 760 V
- 790 V
- 820 V
- 850 V
- 880 V
- 910 V
- 940 V
- 970 V
- 1000 V



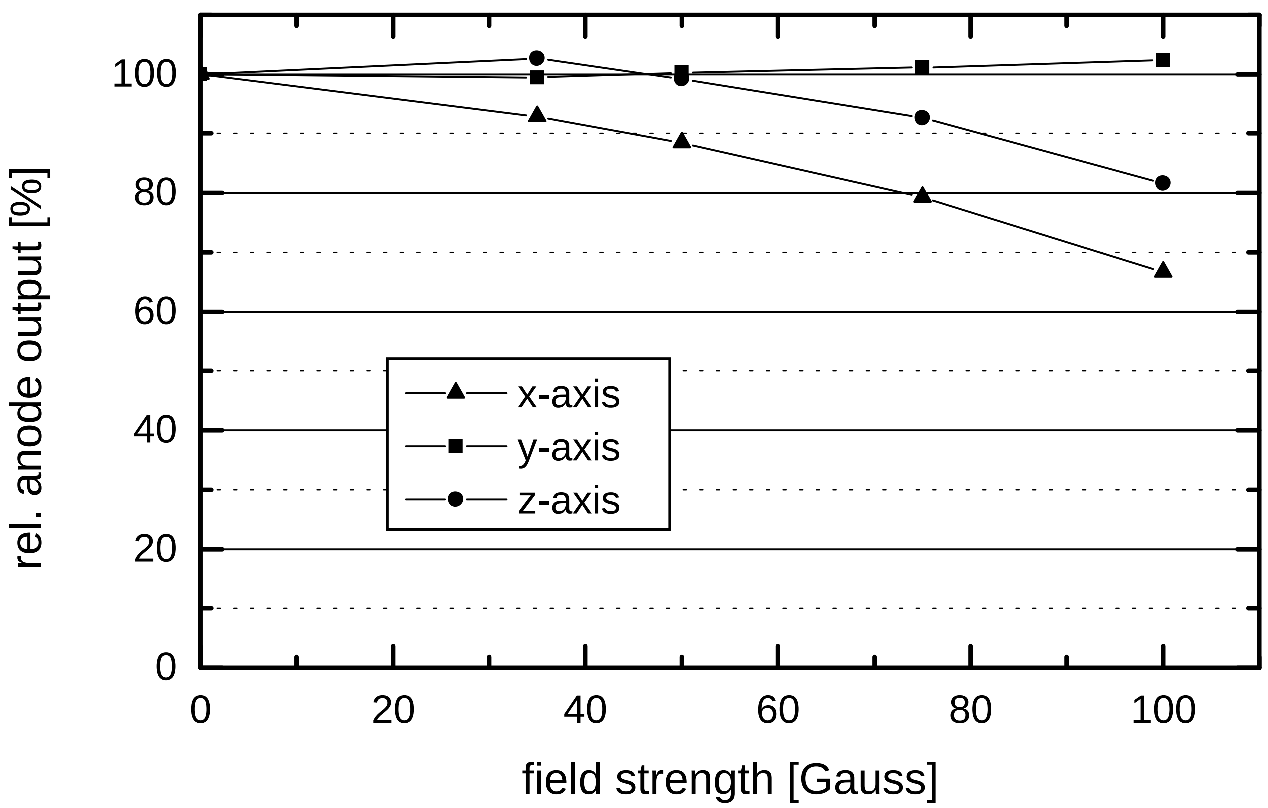
R5900-M 64

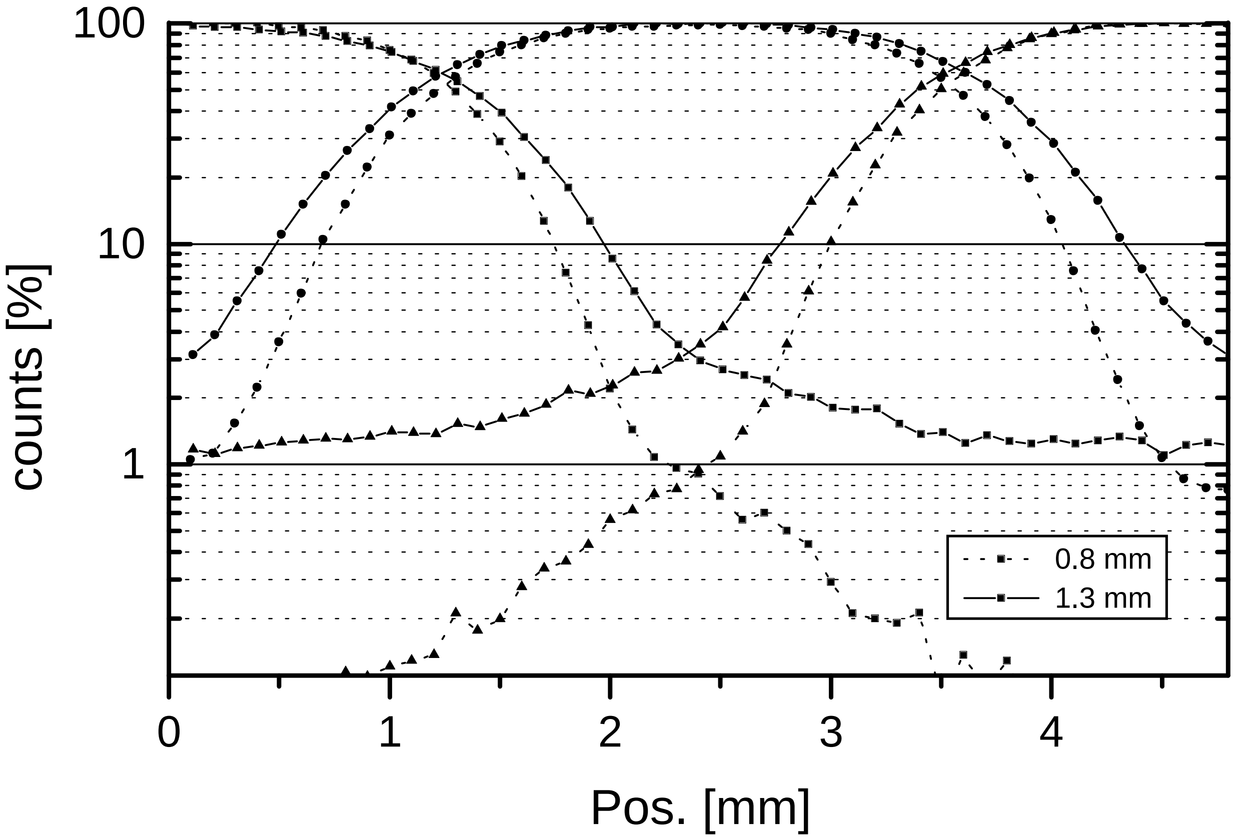


R5900-M 16



cross-talk
0,00
0,02
0,04
0,06
0,08
0,10
0,12
0,75
0,80
0,85
0,90
0,95
1,00
radius of clear fiber [mm]
window thickness
1.3 mm
1.0 mm
0.8 mm
no reflection loss
reflection loss 1 permille
no reflection loss
no reflection loss
reflection loss 1 permille
reflection loss 1 permille


rel. anode output [%]
field strength [Gauss]
x-axis
y-axis
z-axis
0
20
40
60
80
100



100
10
1
counts [%]
0
1
2
3
4
Pos. [mm]
0.8 mm
1.3 mm